

# Bound-free pair production in heavy-ion collisions at high energies

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## **Abstract.**

The electromagnetic process of bound-free electron pair production in heavy-ion collisions at high energies is reviewed. The importance of this process for producing secondary beams is outlined. Single free electron pair production is presented, and the bound-free pair production process is introduced. Double pair production is discussed, and an estimate of the bound-free pair constrained photon-photon luminosity is given.

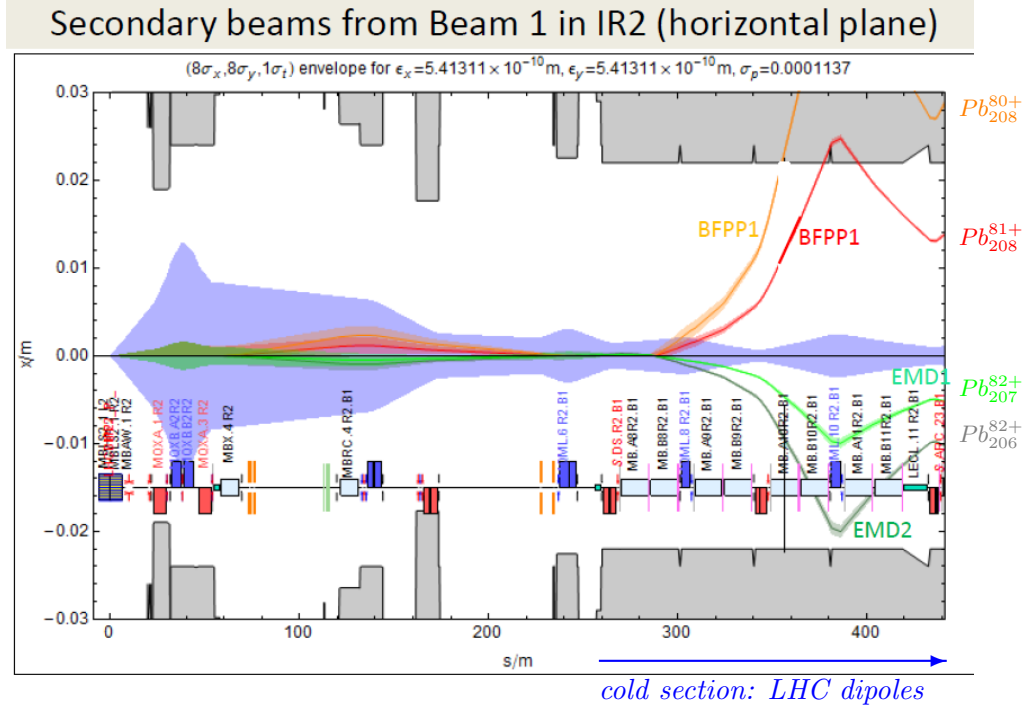
## **1. Introduction**

The process of bound-free pair production in heavy-ion collisions at high energies is of interest both from an experimental and a theoretical view point. From an experimental view point, bound-free pair production is of relevance since it is an important contribution to the life time of a heavy-ion beam at high energies, together with single and multiple neutron emission following Coulomb excitation due to absorption of one or several photons[1]. The bound-free pair process changes the electric charge state of beam particles by one unit, and a secondary beam of different magnetic rigidity is hence emerging from the target position. This secondary beam is transported by the magnets of the beam system, and will eventually hit the vacuum pipe somewhere downstream. Depending on beam species, beam energy and beam intensity, the local deposition of energy at the point of impact might do harm to the vacuum and/or magnet infrastructure, and therefore needs to be studied carefully. The installation of beam collimators at or before the point of impact might be necessary to absorb the energy of this secondary beam [2]. Detectors, integrated into the collimators, and capable of identifying the secondary beam particles on an event-by-event basis, would give access to interesting measurements such as single and double bound-free pair production cross sections.

The process of free and bound-free electron pair production is of electromagnetic origin, and is hence in principle calculable within the framework of QED. The large electric charge of a heavy ion leads, however, to a large electromagnetic coupling at the ion-photon vertex, and the summation of many higher order terms in the perturbation series is needed for getting accurate results. For example, the single free pair production cross section at Born level is modified by substantial Coulomb corrections on the order of 14% at LHC energies [3]. Multiple pair processes, for example production of a single free electron pair in conjunction with a bound-free lepton pair, are also subject to unitarity and Coulomb corrections.

## 2. Secondary Pb-beams at hadron colliders

Electromagnetic processes can result in secondary ion beams originating from the target position. Here, secondary beam refers to beam particles which possess a magnetic rigidity different than the primary beam.



J.M. Jowett, Workshop on photon-induced collisions at the LHC, 4 June 2014

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**Figure 1.** Beam transport calculation of Pb-beams at IR2 of the LHC, taken from Ref. [4]

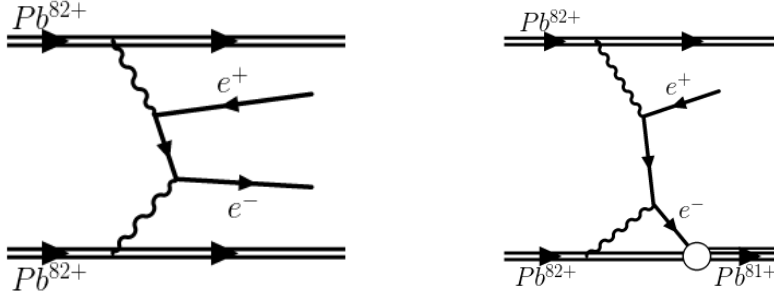
In Figure 1, the transport of the primary and secondary Pb-beams originating from an interaction region (IR) at the LHC is shown. The beams are shown here for the case of IR2, however similar conditions exist at the other IRs. The horizontal scale is shown in units of meters, with the target position located at the origin. The grey shaded boxes at the top and bottom of the plot denote the different magnets of the beam transport system. The cold section of the LHC dipoles starts at a distance of about 260 m from the IR, and is indicated in Figure 1 by a continuous grey shaded area. On the vertical axis, the relative location of the beam and its size are indicated. Here, relative denotes the distance to the beam of nominal momentum  $p_0$  traveling on axis of the magnet beam transport system. The  $8\sigma$  envelope of the primary Pb-beam is indicated by the blue contour. The secondary beam  $Pb_{208}^{81+}$  generated by single bound-free pair production is shown in Figure 1 by the red line labeled BFPP1, whereas the secondary beam  $Pb_{208}^{80+}$  generated by double bound-free pair production is shown by the orange line labeled BFPP2. Similarly, the secondary Pb-beams  $Pb_{207}^{82+}$  and  $Pb_{206}^{82+}$  resulting from one and two neutron emission following Coulomb excitation are indicated by the green EMD1 line and the grey EMD2 line, respectively. These secondary beams will hit the beam pipe at the location of the third or fourth dipole, i.e. in the cold section. At the LHC, there is no space for additional detectors at that location for measuring these secondary beams. Discussions have, however, started for the next generation hadron collider, the Future Circular Collider(FCC), where integration of such detector systems might be feasible if taken into consideration at the early design stage of the machine lattice.

### 3. Single and multiple electron pair production

The strong electromagnetic field of heavy-ion beams results in a variety of two-photon processes. In the Equivalent Photon Approximation (EPA), this electromagnetic field is expressed by the action of an ensemble of equivalent photons [5, 6, 7, 8]. The cross section of heavy-ion induced photon-photon processes can be expressed as

$$\sigma_{PbPb \rightarrow PbPbX}^{EPA} = \iint dn_{1,\gamma} dn_{2,\gamma} \sigma_{\gamma\gamma \rightarrow x}(\omega_1 \omega_2) \quad (1)$$

with  $dn_{i,\gamma}$  the photon flux of beam  $i$ , and  $\sigma_{\gamma\gamma}$  the elementary cross section of the process under study.

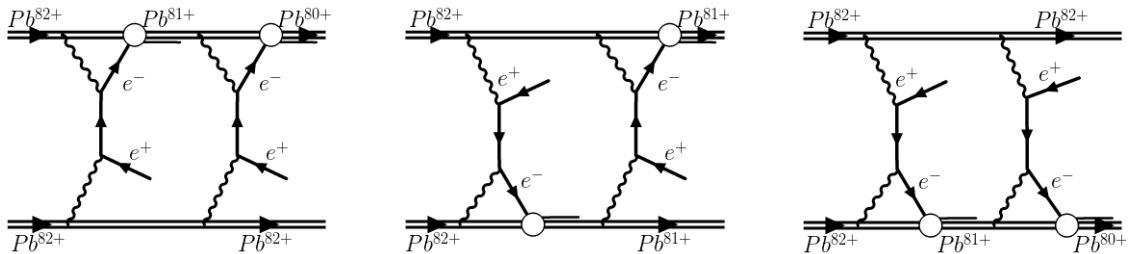


**Figure 2.** Free electron pair production on the left, bound-free pair production on the right.

In Figure 2 on the left, the Born level diagram for free electron pair production is shown. The cross section of this process is given at tree level according to Eq. 1 by integration of the product of differential photon fluxes with the elementary cross section  $\gamma\gamma \rightarrow e^+e^-$ . At LHC energies, the Born level cross section for free electron pair production in the Pb-Pb system is approximately  $\sim 200$  kb. In Figure 2 on the right, the Born level diagram for bound-free pair production is shown. Here, the electron gets bound by the Coulomb potential of one of the Pb-nuclei, resulting in a cross section for production of a Pb-nucleus of charge state  $Pb^{81+}$  of:

$$\sigma_{(PbPb \rightarrow PbPb^{81+} + e^+)}^{EPA} = \int dn_{1,\gamma} \sigma_{(\gamma + Pb^{82+} \rightarrow Pb^{81+} + e^+)}(\omega_1). \quad (2)$$

The cross section for bound-free pair production is calculated according to Eq. 2 by folding the photon flux with the cross section of the elementary process  $\gamma + Pb^{82+} \rightarrow Pb^{81+} + e^+$  [9]. This cross section is approximately 270 b per beam for the Pb-Pb system at LHC energies[10]. Cross section studies differential in the transverse momentum  $p_T$  of the emitted positron have been discussed in Ref. [11].



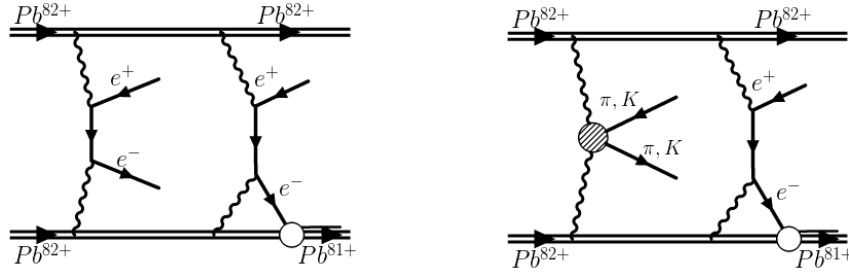
**Figure 3.** Double bound-free pair production: double production on upper beam (left), single production on both upper and lower beam (middle), double production on lower beam (right).

Double bound-free pair production can occur in different configurations. The bound-free single pair production can happen twice on the same Pb-nucleus as shown on the left and right of Figure 3. Here, the final state is composed of the system  $(Pb^{82+} + Pb^{80+})$ . Double production

can also take place as single bound-free pair production on both of the two Pb-nuclei, leading to a final state ( $\text{Pb}^{81+} + \text{Pb}^{81+}$ ) as shown in the middle of Figure 3. The cross section of this process is  $\sigma_{2xBFP}(\text{PbPb,LHC}) \sim 11\text{-}12 \text{ mb}$  [12].

#### 4. Tag on electromagnetic processes

Double production of electron pairs can also take place in mixed form, i.e. production of a free pair in conjunction with a bound-free pair. This process is of particular interest since the forward scattered Pb-nucleus of different charge state carries the tag of an electromagnetic process. This tag can serve a two-fold purpose. First, this tag can be used for the measurement of the single and double pair production cross section. As shown in Figure 1, the secondary beams  $\text{Pb}^{81+}$  and  $\text{Pb}^{80+}$  are separated by a transverse distance of approximately one centimeter at the point of impact, and hence can be identified by detectors with position resolution of order of millimeter. Additionally, the signal from these events can be used as trigger for readout of the midrapidity detectors in the search for triggered two-photon events at midrapidity. Second, if the detector readout is triggered from activity within the midrapidity detectors, or for detector systems with continuous readout, the tag from the forward secondary beams can be used in the analysis of coincidences between forward and midrapidity activity.



**Figure 4.** Double production of free and bound-free electron pair on the left, bound-free electron pair and free pion/kaon pair on the right.

The double production of a free and a bound-free electron pair is shown in Figure 4 on the left. On the right side, double production of a free pion/kaon pair and a bound-free electron pair is displayed. Common to these two different processes is the forward scattered  $\text{Pb}^{81+}$ . The detection of this forward  $\text{Pb}^{81+}$ -nucleus with coincident measurement of central activity hence allows to select two-photon production processes with very small background, an otherwise very difficult endeavour at hadron colliders at high energies.

#### 5. Bound-free pair constrained photon-photon luminosity

A constrained photon luminosity can be associated to each of the forward scattered secondary Pb-beams. This constrained photon luminosity represents the electromagnetic field of the secondary Pb-beam, and expresses the possibility that this electromagnetic field can generate two-photon events by interacting with the electromagnetic field of a nucleus of the other beam. This constrained photon luminosity is dominated by the  $\text{Pb}^{81+}$  beam since the double pair cross section is reduced by at least 4 orders of magnitude as compared to the single pair cross section.

An estimate of this constrained photon luminosity is given below for the case of muon pair production. The differential photon luminosity for free muon pair production is given as

$$\frac{d^2 L^{(st)}}{d\omega_1 d\omega_2} = \frac{d\sigma_{AA \rightarrow AA\mu\mu}}{d\omega_1 d\omega_2 \sigma_{\gamma\gamma \rightarrow \mu\mu}} = \frac{dn(\omega_1)}{d\omega_1} \frac{dn(\omega_2)}{d\omega_2} = \frac{4Z^4 \alpha^2}{\pi^2 \omega_1 \omega_2} \log \frac{\gamma}{R\omega_1} \log \frac{\gamma}{R\omega_2}. \quad (3)$$

The differential luminosity for production of free muon pair plus bound-free electron pair can be expressed as

$$\frac{d^2 L^{bfree}}{d\omega_1 d\omega_2} = \frac{dP_{\mu\mu}(b)}{d\omega_1 d\omega_2 \sigma_{\gamma\gamma \rightarrow \mu\mu}} P_{ee}(b, Z_1, Z_2) d^2 b = \frac{Z^4 \alpha^2}{\pi^4 \omega_1 \omega_2} F(b) P_{ee}(b, Z_1, Z_2) d^2 b, \quad (4)$$

with the function  $F(b)$  defined by

$$F(b) = \int_R^\infty \frac{d^2 b_1 d^2 b_2}{b_1^2 b_2^2} \delta(\mathbf{b}_1 - \mathbf{b}_2 - \mathbf{b}) \approx \frac{4\pi}{b^2} \log \frac{b}{2R}. \quad (5)$$

In the integration over  $b$  in Eq. 5, the main contribution comes from the range  $2R < b < 1/m_e$ , where  $P_{ee}(b, Z_1, Z_2) \sim A = 1.65 \cdot 10^{-3}$  [12].

Substituting into Eq. 4 yields

$$\frac{d^2 L^{bfree}}{d\omega_1 d\omega_2} = A \frac{4Z^4 \alpha^2}{\pi^2 \omega_1 \omega_2} \left[ \log \frac{1}{2Rm_e} \right]^2, \quad \frac{d^2 L^{bfree}}{d\omega_1 d\omega_2} \sim \mathcal{O}(10^{-3}) \frac{d^2 L^{st}}{d\omega_1 d\omega_2}, \quad (6)$$

hence the bound-free constrained photon luminosity is reduced at order  $\mathcal{O}(10^{-3})$  as compared to the standard photon luminosity.

## 6. Discussion

The possibility of measuring secondary Pb-beams generated by bound-free electron pair production in coincidence with additional two-photon processes addresses a list of physics issues.

- The cross section for bound-free pair production in heavy-ion collisions can be calculated at tree level according to Eq. 2. This cross section is modified by higher order terms due to unitarity and Coulomb corrections.
- Double bound-free pair production is possible in different configurations as discussed above. The measurement of the cross section of the  $(\text{Pb}^{82+} + \text{Pb}^{80+})$  and  $(\text{Pb}^{81+} + \text{Pb}^{81+})$  final state permits to test whether  $\sigma(\text{Pb}^{81+} + \text{Pb}^{81+}) \sim 2 \times \sigma(\text{Pb}^{82+} + \text{Pb}^{80+})$  as derived in the impact parameter representation [12]. The measurement of these two cross sections allows to test the contributions of unitarity and Coulomb corrections to these two different final states.
- Multiple production of  $N$  lepton pairs can be of mixed form, i.e. bound-free pair production with production of  $N-1$  free lepton pairs [13].
- Double pair production can be of mixed form, i.e. bound-free pair production in association with a pion or kaon pair.
- Multiple interactions can be of mixed form, i.e. bound-free pair production in association with photoproduction of a resonance, for example  $\eta, \eta'$ .
- Multiple interactions can be of mixed form, i.e. bound-free pair production in association with two-photon processes beyond the resonance region.
- Multiple interactions can be of mixed form, i.e. bound-free pair production in association with two-photon processes  $\gamma\gamma \rightarrow \gamma\gamma$ . This two-photon scattering receives contributions from lepton loops, quark loops, and, possibly, the monopole loop [14],[15],[16].

- Multiple production of lepton pairs can be accompanied by internal excitations of the nucleus, either in an intermediate state between two photon exchanges, or in the final state. The contribution of virtual internal excitations to the double bound-free cross section is estimated to be  $< 25\%$  which is well within the accuracy of the present calculations [12]. Excitations of the final state  $\text{Pb}^{81+}$  result with high probability in the emission of one or several neutrons, and lead to the generation of additional secondary beams. The experimental detection of hybrid beams such as  $\text{Pb}_{207}^{81+}$  and  $\text{Pb}_{206}^{81+}$  depends on the beam optics, and on the placement of the detectors used for secondary beam detection.

The approach of measuring these reaction channels in coincidence with the bound-free produced  $\text{Pb}^{81+}$  is expected to result in a much improved signal to background ratio. In this approach, the coincident count rate is, however, reduced by the factor of bound-free constrained to standard photon luminosity. As derived above, this reduction factor is, for example, estimated to be on the order  $\mathcal{O}(10^{-3})$  for free muon pair production. This reduction needs to be evaluated for each measurement above individually due to the different cross sections involved.

## 7. Summary and outlook

The process of single and double-bound free pair production in heavy-ion collisions at high energies is reviewed. Double pair production in mixed form of free pair and bound-free pair is discussed. The experimental constraints of such measurements are summarised.

## 8. Acknowledgements

The author gratefully acknowledges fruitful discussions with Valeriy Serbo, Otto Nachtmann and John Jowett on issues presented in this study. This work is supported by the German Federal Ministry of Education and Research under promotional reference 05P15VHCA1.

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